INTERNATIONAL ENERGY AGENCY (IEA)
SMALL SOLAR POWER SYSTEMS PROJECT (SSPS)

THE IEA / SSPS SOLAR THERMAL POWER PLANTS

Volume 1: Central Receiver System (CRS)

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THE IEA/SSPS SOLAR THERMAL POWER PLANTS
– Facts and Figures –

Final Report of the
International Test and Evaluation Team (ITET)

Editors:
P. Kesselring and C. S. Selvage

Volume 1:
Central Receiver System (CRS)

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INTERNATIONAL ENERGY AGENCY / SMALL SOLAR POWER SYSTEMS (SSPS)

EVALUATION REPORTS

1. INTRODUCTION

This introduction to the final evaluation report of the SSPS International Test and Evaluation Team (ITET) is split into two parts: The first part -written by the head of the Test and Operation Advisory Board (TOAB)- gives a picture of the SSPS evaluation effort as seen from the point of view of an observer far away from the project site in a participating country. The second part -written by the head of the International Test and Evaluation Team (ITET)- gives the general project overview.

1.1 The SSPS Project evaluation, as seen by the head of the TOAB

a) Structure and interaction of ITET and TOAB

In retrospect, the most astonishing feature of the SSPS Project to me is that it was possible to integrate the quite different interests of nine countries to the extent that such a large common venture -worth approximately 90 Million DM- could be realized. This general aspect -i.e., the need to integrate different, sometimes conflicting interests- was also of importance when it came to the organization of the project evaluation. It is e.g., reflected in the structure of the ITET. Only its head and the two senior evaluators were direct "employees" of the Project. All other members were seconded by the different countries to the Project. Their selection, in the countries, was only restricted by relatively loose boundary conditions, set by the Project (minimal duration of stay, minimal number of members to be seconded by a country, preference for certain qualification profiles). As a result, the ITET was a frequently changing group of people, differing not only in nationality but also with respect to the background of education and interests. It was held together by the common task.

While ITET members during their stay in Almería worked full time and on site for the project, many members of the Test and Operation Advisory Board (TOAB) devoted a few days per year only to SSPS activities. The members of this board were designated by their countries in order to help the project with their professional expertise and at the same time to articulate the interest of their countries on a technical level. Thus, in making a main contribution to the definition of the evaluation program, the TOAB selected from the very large number of imaginable R&D subjects, a small fraction, lying within reach of the ITET and reflecting the technical priorities as well as the national interests.

The interaction between TOAB and ITET -whose head and senior evaluators as well as the OA, took part in TOAB meetings ex officio- led to very beneficial side effects: The ITET, struggling with the daily on site problems, could not forget about the needs of the far away home countries and the sometimes (too) high expectations of the TOAB were brought down to the reality of the hard facts in Almería.

b) Structure and character of the ITET Final Evaluation Report

Thus, the stage was set for the final evaluation. It was carried out in the following way: The evaluation topics defined by the "deliverables" were discussed within the ITET and subtasks assigned to the members of the group. The responsibles for each subtask then became the authors of a self-consistent paper, describing their work, results and conclusions. It is the collection of all these individual papers -written within the common framework explained before- that forms the main body of the Final Evaluation Report of the ITET.

The history of the report makes it clear that one should not expect a homogeneous document, covering every possible R&D aspect of the two plants in a comprehensive way. What we must expect and find, is consistency between the different contributions and their conclusions. A variation in the depth and quality of treatment is obvious and finds its natural explanation in the fact that the spectrum of authors begins with engineers, recently graduated from engineering schools, and ends with professors from technical universities. The reader, missing a paper on a topic of high interest to him, must be reminded that time and resources were limited and obviously any selection of priorities is debatable to some degree.

c) The Information Pyramid

Even considering these restrictions, the present volumes contain a very large amount of very valuable information concerning solar thermal power plants. In order to manage this information avalanche efficiently, we have introduced a hierarchy of publications, which we call the "information pyramid". It begins at the top with a book giving a synthesis of the SSPS work in the context of solar thermal power plant development in general. The book makes reference to the present collection of papers frequently. It also appears in a Springer edition and is written by an author hired by the project. The language is such that students and young engineers will be able to follow and the mature engineer gets a quick overview of the important aspects of the solar thermal technology.

The reader, willing to go into more detail, may then take the "Book of Summaries", containing the abstracts of all the papers included in the 3 volumes of the ITET Final Report. He thus has the possibility to decide quickly which of the references given in the book are most important to him and whether or not he should dig into the thick volumes in order to study the complete papers. Complete papers make reference to SSPS Technical Reports and/or to the lowest level, the SSPS Internal Reports. This information as well as raw data are available upon request via the Executive Committee members. Thus, there is a simple and efficient way to get down from the most general, highly aggregated information into more detail, step by step, to end up with the raw data, if necessary.

In parallel to the ITET's Report, the Operating Agent's point of view of the SSPS Project is given in his final report (SR-7: SSPS - Results of Test and Operation, 1981 - 1984).

d) Lessons learned

Concluding my part of the introduction, I would like to give a short, personal view of the lessons learned from the existing solar thermal power plants in general and the SSPS Project in particular. Such statements are necessarily simplifying and incomplete but nevertheless, useful in characterizing the status of a development at a given point in time 1):

- The development of the solar specific components and subsystems of solar thermal power plants during the last 8 years has been a technical success. Receivers, collectors and heliostat fields perform to a large extent as expected.
- The problems arising from solar specific systems aspects have been underestimated. We mention in particular:
  - Start-up, shut-down time of plant (transient behavior)
  - Heat energy management in storage systems
  - Troubles with "from the shelf" components and subsystems.

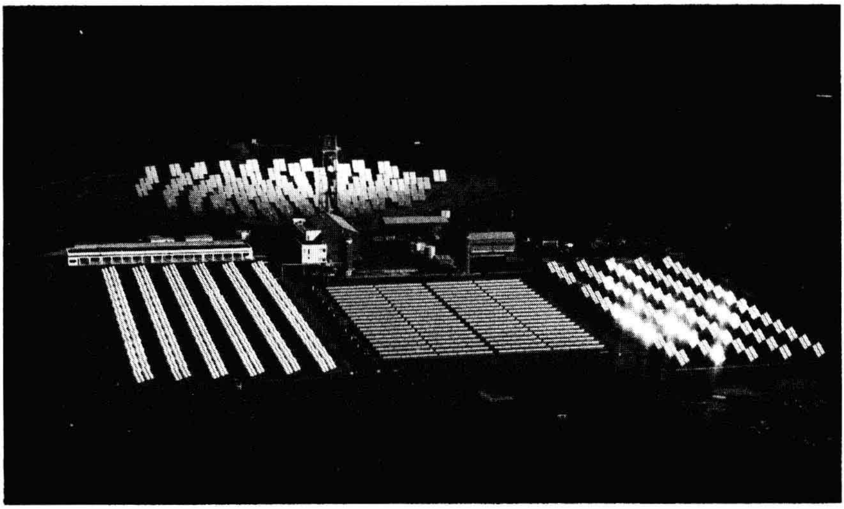
  They have been the source for a great part of the difficulties encountered in the existing prototype plants.
- These problems are manageable and can be handled by good design including in particular
  - fast "first stages" (receiver + energy transport system to storage and e.g., steam generator)
  - higher solar multiples and storage
  - carefully chosen power conversion systems, matched to the solar specific requirements of the plant as a whole
  - larger plants (e.g., $\gg$30 MW(el))
  - minimizing plant internal consumption (10% of the annual gross output seems to be a feasible goal for larger plants).
- Site selection is very important. Local meteo conditions must be evaluated carefully. On site measurements of direct normal radiation are necessary before final site selection. Mean values are not sufficient, information concerning the intensity distribution in time is required.

In conclusion, we may say that when we started the design of the present generation of solar thermal plants in the mid-seventies, we thought that we would demonstrate commercial operation on a small scale. We were too optimistic. As a matter of fact, we have been one plant generation further away from commercial operation than we thought at the time. This is the reason why I call existing plants "prototype plants" or "experimental plants" and not "pilot plants" as it is usually done. However, if the lessons learned from the existing experimental plants are incorporated properly into future designs, a satisfactory performance of commercially sized future demonstration plants may be expected now.

1) Statements taken from a lecture given at the 2nd Igls Summer School on Solar Energy 1985, 31.7-9.8.1985 (Papers to be published by ESA)

1.2 Introduction to the SSPS Project

One objective of the International Energy Agency's (IEA's) energy research, development, and demonstration (R§D) program is to promote the development and application of new and improved energy technologies which could potentially make a significant contribution to our energy needs. Towards this objective,the IEA has established and conducted energy research, development, and demonstration projects, one of which is the Small Solar Power Systems (SSPS) project built in the province of Almeria, Spain. This project, performed under the auspices of the IEA by nine countries (Austria, Belgium, Switzerland, Germany, Spain, Greece, Italy, Sweden, and United States of America), consisted of the design, construction, testing, and operation of two dissimilar types of solar thermal power plants: a distributed collector system (DCS) and a central receiver system (CRS). They are constructed adjacent to each other on the Spanish Plataforma Solar in Almeria, southern Spain. Both have the same rated electrical output (500 kW_e design at equinox noon) and have delivered electric energy to the Spanish grid during the three-year period 1981 - 1984.



SSPS PLANT

The SSPS plant operation has produced several unique observations.

* Operational experience has been observed with the functioning of a DCS and CRS power plant.

* Different designs of advanced solar technologies (collectors, heliostats, receivers, storage systems) have been tested comparatively as part of a complete power plant system in different operational modes.

* The grid environment of the Plataforma Solar north of Almeria, with statistically the highest solar irradiation of southern European countries is representative of a wide range of future applications of solar power plants.

* The conventional part of the SSPS power plants, which is the power conversion system, has been tested with respect to its viability for solar applications.

The principal objective of the SSPS project was to examine in detail the feasibility of using solar radiation to generate electrical power. In addition, the project had the following objectives:

* Promote cooperation between IEA members in the field of new technologies.

* Demonstrate the technical feasibility of designing and building solar power plants with available hardware.

* Gather operational performance data on such plants.

* Evaluate the viability of the DCS and CRS concepts.

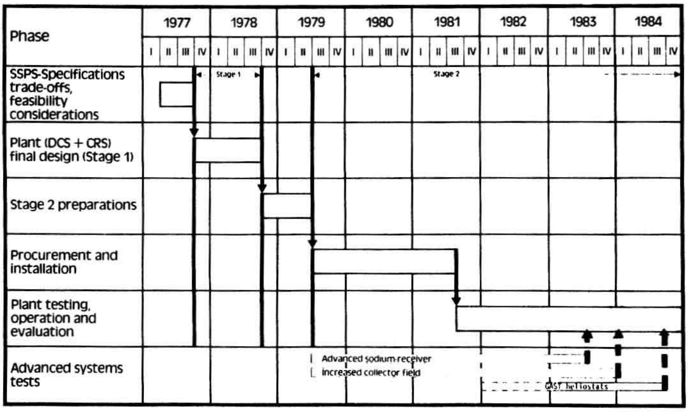
* Design a plant that was optimized to 500 kW_e, but which had the potential for being scaled up or down.

* Consider different geographical applications and operational modes.

* Minimize the investment costs while achieving reasonable operating expenses, good engineering safety, and a long lifetime.

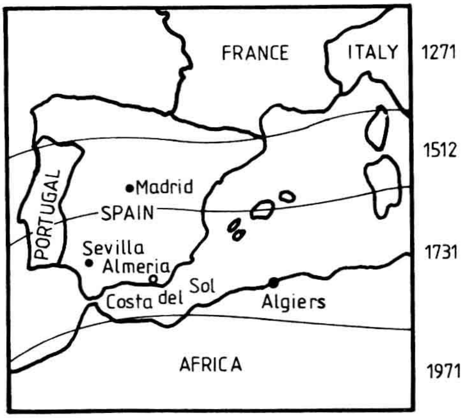
* Assess the further technical development of solar power plants.

The project consisted of two phases: Phase 1 - the erection of the CRS and DCS system, and Phase 2 - test and operation. The project time schedule shows the main events before and during those two years.



SSPS Site Location

This particular site was chosen for its geographical characteristics and because this region of Spain promised favorable conditions relative to the annual amount and intensity of solar insolation.



Test and Operation Organization

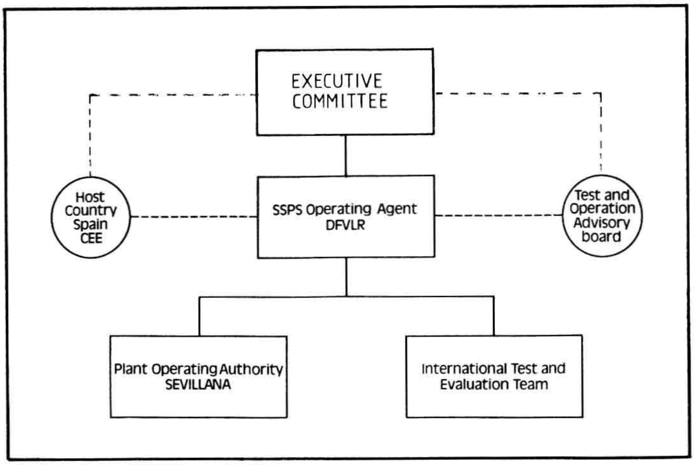
The testing and operation phase, which was conducted over a period of three years, was organized to collect data on:

- the viability of the selected technical solutions,

- the operational behavior of the systems, and

- the economics of the plants.

This phase of the project was administered by the organizational scheme shown below.



Within this organizational structure, the DFVLR (Deustche Forschungs-und Versuchsanstalt für Luft-und Raumfahrt e.V) served as the Operating Agent and was responsible for carrying out the SSPS project on behalf of the SSPS participating countries. The operational and evaluation activities to be performed were specified in a Basic Test and Operation Program document, as well as yearly updates called the Program of Work. The operation of the SSPS-CRS and -DCS was performed by the regional Spanish utility Compania Sevillana de Electricidad, acting as the Plant Operation Authority.

The scientific testing and evaluation work was entrusted to an international test and evaluation team (ITET) composed of experts from the participating countries that conducted on-site tests and analyses. The ITET was established by the Executive Committee and was headed by Mr. C. S. Selvage. This on-site team has evaluated and reported on test and operation activities and has recommended and advised the plant director on defining, planning, preparing, and conducting tests and operations. The team has performed such functions as:

- recommend tests and modes of operation for the plants
- define criteria to be met for tests and modes of operation and data requirements
- review testing, operation , and maintenance data to assess the validity of the data and potential needs for further data or retesting
- evaluate and report on the results of operation and special tests
- compare the performance of the plants when operating in similar modes of operation
- provide ad-hoc engineering support to the Operating Agent
- at a system level, compare actual performance with design goals
- at a subsystem level, compare the actual performance of the major subsystems with the design goals
- assess the reliability of the various components and subsystems based on an analysis of data.

To summarize, the evaluation consisted of combining and comparing measured, calculated, and reported plant data to determine the plant's performance and behavior over the entire period of the program. The results of these evaluations performed by the ITET have been reported in SSPS technical and internal reports, a listing of which is presented in Appendix A. In addition, four international workshops were conducted on site in order to present the status of the ITET work.

The following are a compilation of new and previously reported studies that represent work done by the ITET performing evaluations of various aspects of both systems that were requested by the TOAB and the Executive Committee. The investigations related to the CRS are described in Volume I of this report; those for the DCS are described in Volume II; and the Site Specific work is in Volume III.

The ITET staff in the years 1981 through 1984 were:

C. Gomes Camacho	Spain	June 1981 - June 1982
A. Baker	USA	summer 1981
R. Stromberg	USA	summer 1981
W. Wilson	USA	summer 1981

M. Loosme	Sweden	September 1981 - June 1983
P. Wattiez	Belgium	September 1981 - December 1984
T. von Steenberghe	Belgium	September 1981 - August 1983
F. Gaus	Germany	December 1981 - December 1983
C. S. Selvage	USA	January 1982 - March 1985
P. Toggweiler	Switzerland	January 1982 - August 1982
H. Jacobs	Germany	February 1982 - March 1985
R. Carmona	Spain	July 1982 - March 1985
M. Pescatore	Switzerland	July 1982 - May 1984
M. Anderson	Sweden	January 1983 - December 1984
J. Martin	USA	May 1983 - December 1984
F. Palumbo	Italy	May 1983 - November 1983
M. Blanco	Spain	January 1984 - March 1985
M. Sanchez	Spain	January 1984 - March 1985
J. Sandgren	Sweden	April 1984 - January 1985
A. De Benedetti	Italy	March 1984 - December 1984
N. Gregory	Switzerland	June 1984 - October 1984
B. W. Swanson	USA	September 1984 - November 1984
W. Schiel	Germany	Part of 1983 and fall 1984
G. Lemperle	Germany	Fall 1984
A. Brinner	Germany	Part of 1983 and 1984

The following specific evaluation reports make up VOLUME I, which is the evaluation of the CENTRAL RECEIVER SYSTEM. This evaluation report VOLUME I, contains reports of thirty (30) specific evaluations of six specific evaluation topic areas referred to as SECTIONS. The evaluation topic areas, by section titles are:

SECTION 3- HISTORICAL ASSESSMENT OF THE SSPS CRS PLANT PERFORMANCE.
SECTION 4- HELIOSTAT FIELD PERFORMANCE.
SECTION 5- RECEIVER BEHAVIOR.
SECTION 6- THERMAL LOSSES/THERMAL INERTIA.
SECTION 7- SYSTEMS ASPECTS/CONTROL.
SECTION 8- POTENTIAL FOR IMPROVEMENTS

A summary of each of the specific evaluation reports and the conclusion of that evaluation is contained in the introduction for each of the sections. The overall conclusions for this project are contained in the foreword.

2. CENTRAL RECEIVER SYSTEM

The 500 kW_e CRS plant has a north field of heliostats directing reflected solar energy to a tower mounted receiver. Thermal energy from the receivers is piped to a hot storage tank and then to a steam generator which produces superheated steam. This superheated steam is fed to a steam motor to produce mechanical energy to drive an electric generator. The CRS plant consists of three major systems: a heliostat field, a sodium heat transfer system, and a power conversion system. A simplified process flow diagram of these systems is shown in Fig.2.-1. The CRS main design features are given in Fig.2.-2 and system data in Figure Fig.2.-3.

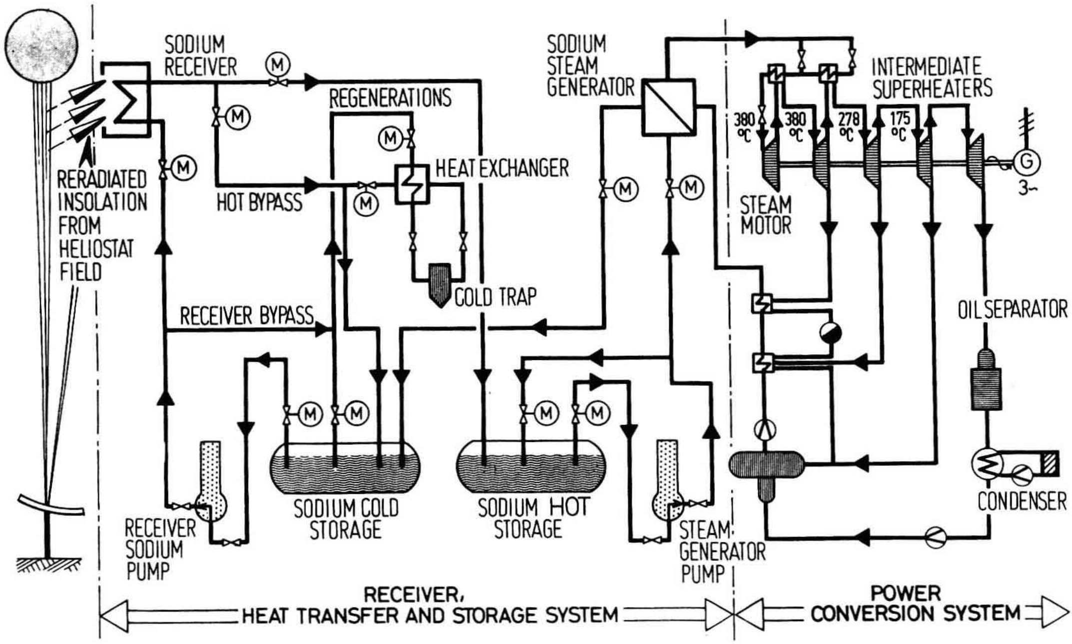


Fig.2.-1: Simplified CRS Process Flow Diagram

Heliostats	Martin Marietta Barstow, 3360 m^2 total reflective area
Receivers	1) Cavity Type with an octagonal shaped aperture of 9.7 m^2; peak heat flux on absorber tubes 62 W/cm^2; inlet / outlet temperature 270/530°C 2) External type with 2.85 x 2.73 m aperture and five panels, each with 39 parallel tubes; peak heat flux 140 W/cm^2
Heat Transfer System	Liquid Sodium
Storage System	Two tank storage equivalent 1 MW_e
Power Conversion System	6-piston steam motor (Spilling), cycle efficiency 27.2% (calculated)
Safety Precautions	Uninterruptable power supply, sodium/waterreaktion and sodium fire protections, lightning protection, design according to possible seismic events
Performance	517 kW_e net output at equinox noon
Design Lifetime	10 years
Guarantee	90% performance guarantee at design point

Fig. 2.-2: CRS Main System Design Features

Design Point	Day 80, 1200 (equinox noon)		
	Solar insolation, kW/m^2	0.92	
Heliostat Field	93 heliostats		
	Total reflectice surface area, m^2	3660	
Receiver	Aperture size, m^2	9.7	
	Active heat transfer surface, m^2	16.9	
	Inlet temperature, °C	270	
	Outlet temperature, °C	530	
	Efficiency (calculated), %		85
2nd Receiver	Aperture size, m^2	7.91	
	Active heat transfer surface, m^2	7,91	
	Inlet temperature, °C	270	
	Outlet temperature, °C	530	
	Efficiency (calculated)		94
Thermal Storage	Storage medium		sodium
	Thermal capacity, MWh		5.5
	Hot storage temperature, °C	530	
	Cold storage temperature, °C	275	
Steam Generator	Sodium inlet temperature, °C	525	
	Sodium outlet temperature, °C	275	
	Water inlet temperature, °C	190	
	Steam outlet temperature, °C	510	
	Steam pressure, bar	100	
Power (at design point)	Solar input to receiver (insolation), kW		2880
	Thermal input to steam motor (thermal), kW		2200
	Gross electric, kW		600
	Net electric, kW		517
Efficiencies (at design point)	Thermal to gross electric, %		27.3
	Thermal to net electric, %		23.5

Fig.2.-3: Main System Design Data for CRS

The heliostat field subsystem includes the heliostat field and associated controls. The Martin Marietta heliostats used are identical to those at the 10 MW_e Barstow Pilot Plant except that the curvature of the mirror has been increased to shorten the focal length. Each heliostat has a reflective area of 39.3 m^2. The field consists of 93 heliostats with four different focal zones. Fig.2.-4 gives the heliostat field focal zone definition and shows the concentric-circle layout of the field north of the receiver tower. The mirror module is a vented sandwich design of hot-bonded glass mirror, honeycomb core, and steel pan enclosure. The heliostats are controlled by the heliostat array controller (HAC) located in the main control room. The HAC transmits commands to the heliostats via four heliostat field controllers (HFC). Each of these HFC's acts as a heliostat controller (HC) for four heliostats and also transmit data to other HC's which are located on each heliostat. All heliostats had the same aim point on the cavity receiver near the center of the receiver aperture. With the Advanced Sodium Receiver (ASR), three aiming points were used in order to provide a balanced thermal input.

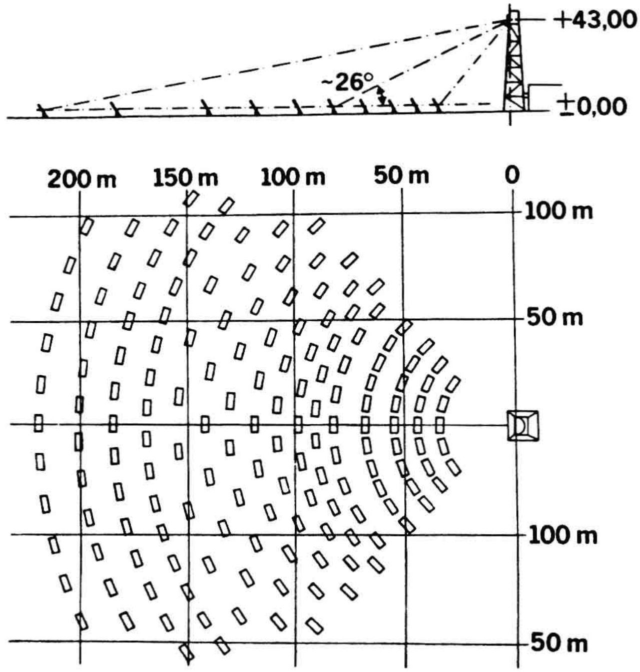


Fig.2.-4: Heliostaat Field Layout

Two receivers were installed at the CRS. The first receiver was a north-facing cavity type with a vertical octagonal shaped aperture of 9.7 m^2. The absorber panel is a 120-degree segment of a right circular cylinder. Sodium flows in six horizontal parallel tubes, which are 38 mm in diameter and -1.5 mm wall thickness, which serpentins from near the bottom of the cavity to the top defining the absorber panel. These tubes are not joined (welded) along their length but are supported by mechanical means. Sodium enters the inlet header at 270°C located at the bottom of the panel and exits the outlet header at 530°C near the panel top. The location of the absorber panel inside the cavity is such that the peak heat flux is about 62 W/cm^2 at equinox noon when 2880 kW_{th} enters the cavity aperture.

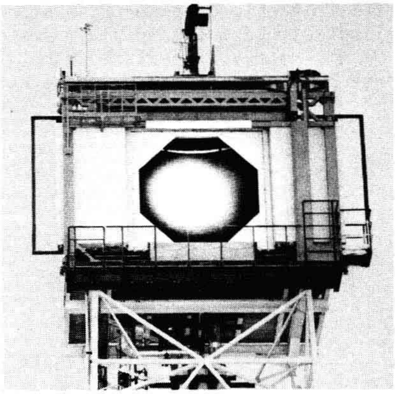


Fig. 2.-5: Cavity Receiver (Sulzer)

The second CRS receiver was a 2.7 MW_{th} external type that consists of five panels arranged to form a rectangular absorber 2.85 m high and 2.78 m wide. Each panel consists of a tube bundle with 39 - 14mm diameter vertical tubes, a bottom and top header and a downcomer. The flange of the bottom inlet header and the restraint at the downcomer sodium outlet are attached to the panel. The top header moves vertically to accommodate vertical thermal growth of the panel. The irradiated tubes are assembled together in groups of three and held with four supporting plates to form a 'triplet'. These triplets are connected to the panel framework by means of pins such that the tubes can grow axially with respect to the frame and also rotate, because of the clearance between each pin and its hole in the triplet supporting plate. Gaps are provided between so that each triplet is free to expand independently in the horizontal direction. Liquid sodium is pumped from the cold storage tank at 270°C into the bottom of receiver panel at one edge, through each of the panels in series and out at the top of the central panel at 530°C.